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NEW APPLICATIONS FOR ARPANET DEVELOPED INFORMATION PROCESSING TECHNOLOGY. VOLUME III. BRIAREUS - COMPUTER NETTING FOR DESIGN, FABRICATION AND REPAIR OF ELECTRONIC EQUIPMENT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Discusses fabrication of high technology electronics equipment, particularly digitally based systems, by specifying, designing and fabricating equipments on a fully automated basis. A hypothetical universal machine is proposed, operating under computer netted control, combining developments in the automated design, numerical control, and integrated circuit packaging fields. The intended results include computer-engraved PC boards, computer modified equipment, automatic testing, engineering design change drawings, computer repair & maintenance, and computer-made, fully assembled printed circuits at remote locations.

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PREFACE

The work of this overall project is the search for new applications for computer resource sharing made possible by developments in computer communications by ARPA/IPTO and others. To this end we have delineated a number of potentially very high payoff areas for the future.

In Volume I of this study we examined some of the impacts and savings and improved efficiency that can occur in using a fully developed interconnected computer based system to aid the rationalization of the management of the procurement process. Volume I showed that significant savings could be made in procurement, and that particular attention should be given to high dollar, non-RDT&E, high technology, single source procurements. Information automation was shown to be able to increase competition and reduce lead time. One major cost factor in defense procurement is attributable in part to the "locked-in" position that an electronic system supplier invariably achieves in large system developments because of the high rates between fixed and variable costs in present production of defense electronics. This competition-discouraging factor causes most large, high technology equipments to be procured almost entirely by negotiated sole source procurements. Even the residual occasional advertised bid procurement is regarded by many in the industry as an opportunity to "buy in" to set up the winner as a later sole source supplier.

The high or fixed cost for manufacturing defense electronics has some unpleasant dimensions that work against national security. Consider the positions of the leading Western World nations presently competitively marketing their weapon systems to developing coutries with inadequate concern given as to how these weapons would be used in the longer term. The past rationale for selling weapons was to support friendly governments threatened by less friendly ones in the interest of world peace. This motivation appears to be giving way to a less satisfying economic force balancing foreign exchange (primarily for importation of petroleum) and increasing the production quantities of weapons manufactured to better amortize fixed costs and thereby reduce the per item cost. This approach holds the long term price for

a short gain somewhat similar to what might have occurred if the 19th Century U.S. cavalry was funded from the revenues of sales from firewater and guns to the Indians.

The issue that we address in this volume is that of seeking to significantly reduce the cost of small production run, high technology military electronic equipment. Defense electronics is a $15.3 billion per year budget expenditure. Even saving a small percentage of this can be shown to have a high payoff. We consider some impacts that computer communications systems can make to certain electronic fabrication processes in general, with significant particular benefit to the Department of Defense.

CONTENTS

Appendices:

INTRODUCTION

In this volume we explore a new way for fabricating high technology electronics equipment. We are particularly interested in digitally based systems. Here turn-around time is important, production runs short, and demand for specialization high. As the percentage of digital to non-digital circuits increases, it becomes increasingly feasible to specify, design and fabricate equipments on the fully automated basis to be described.

To be usefully specific we shall examine a single thread in a larger fabric; one hypothetical overall system implementation out of many possible. Our objective is to discuss problem areas. We then show what is contemplated may be within our grasp, provided the necessary research and development is undertaken.

Having done so, we then consider applications, benefits and the benefit-to-cost ratio that appears to us to characterize this potential domain of effort.

To focus the discussion in "straw man" fashion, we start by proposing a specific hypothetical new universal machine — a multi-armed Briareus* operating under computer netted control. We seek to combine developments in the automated design field, plus developments in numerical control, plus developments in integrated circuit packaging and automated testing. If successful, the result will yield a set of new capabilities including:

1. Means to use a programmed computer to electrically store all the information required to engrave a printed circuit board.

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*Briareus — from Greek mythology; first of the 100-armed giants. We use the name to refer to a computer controlled fabrication system using a plurality of separate fabricating elements.

2. Provision for insertion and removal of electronic components without permanent damage, under computer control without manual intervention.

3. Provision for automatic testing of all components to be inserted into the board and prevention of placement of defective components on the board.

4. Provision of means to draw patterns on paper as a design aid with the same mechanism used to make printed circuits to facilitate engineering design changes.

5. Provision for using the same equipment as used for construction for repair and maintenance under computer control and without manual intervention.

6. Provision for operation of the system by telecommunications, so that locally inputted design information may be used to create fully assembled printed circuits at remote locations.

In the following section, DESCRIPTION, we briefly describe the Briareus concept in terms of how it would be built and how it would work. In the next section, APPLICATIONS, we consider how it could be used. The final section, ECONOMIC ANALYSIS, consists of estimates of performance and payoffs.

Since we wish to assure ourselves that what we are describing is fully possible, we have prepared a detailed first-cut description of the machine in patent specification detail.

As an appendix, we include a working paper, "On Improving Processing Capability of Infinitely Variable Interconnection Path Storage: The Concept of Medium Versus Message Storage," to provide what we hope is a useful insight into use of the proposed technology for the creation of new forms of computer system architecture. Lastly, there is a bibliographic appendix describing the state of the art in technologies related to Briareus.

Much of this volume constitutes an existence proof, suggesting that there are no obvious reasons that the Briareus system cannot work. Further, it seeks to suggest that such a system can be built with elements within the component state of the art. The operating cycle times are estimated and the resulting hourly cost of the machine is then shown to be equivalent to that of a single technician, while productivity increases by a factor of perhaps 10 to 100.

What we propose is not a panacea for all electronics assembly. However, we believe it can make a significant impact on the quality and timely availability of a broad class of electronic circuitry. There will always remain applications for which it is not appropriate; but even the questions of where it will and will not fit constitute an important discussion. Discovering the bounds where this new technology is applicable strikes us as a very fruitful new direction of research — with a very high payoff, plus a good chance for success.

DESCRIPTION

FORMAT OF THE INVENTION

This section is written in the style of a patent specification. The patent style, while a little awkward to read by one not familiar with it, is a very useful way of describing new systems. The format insures that the notions are sufficiently detailed and complete that no major element required for operation is overlooked. While it is not Cabledata's intention to file for patents at this time, it should be mentioned that the U.S. Government holds unlimited rights to any invention that results wholly from their contracted work.

The description in the next several subsections, particularly that involving the figures, is so detailed that it may tell some readers more than they want to know about the subject. For these readers, we suggest that they turn to the next sections, starting with APPLICATIONS on page 28.

BACKGROUND OF THE INVENTION

Field of the System

This system relates to mechanisms for design and complete fabrication of electronic equipments, in particular those using plug-in, dual in-line packages (DIPS).

Description of the Prior Art

The manufacture of printed circuit boards using numerical controlled drilling and routing machines is well known. Computer-aided logical design and, to a limited degree, automatic circuit board layout methods are in present use. Electronic component insertion machines operating under tape control are also in present use. Generally, their use is limited to mass production

applications where a few components are inserted at one time into a printed circuit board. Automatic fault detecting equipment for discovery of faults in DIP and other integrated circuits is also well known, as are computer networks, microprocessors and other sectors of the computer art that will be referred to in the following.

The limitations of the present art of interest is that no single piece of equipment exists for performing all the many steps required to convert a circuit description into physical operating electronic equipment. The present art of circuit fabrication invariably calls for wet chemical processing. Further, no system has been described in the literature which combines all the non-obvious steps together which permit a fully automated, low set-up time, low overhead facility for the production and repair of electronic equipment in small quantities, in a cost effective manner.

SUMMARY OF THE SYSTEM

The Briareus is built around a rigid work table with dimensions approximately those of a conventional laboratory bench, but heavier and more rigid. The work table is a single movable work surface translatably movable in two orthogonal axes parallel to the work table.

The name Briareus refers to the multi-armed nature of the machine, where each of a number of fabrication arms are independently and sequentially moved in relation to a common work piece. In the initial design, a single moving table transports a printed circuit board to be fabricated from each arm position to the next. Each drill, or router, moves up and down through a very small, preset distance. By routing narrow non-conductive paths through the copper surface of a blank printed circuit board, precision conductive paths can be formed. The position of the arms are generally referenced to position of the single moving work surface. Each arm would be operated sequentially, although parallel operation is possible. The board is positioned by the movable table from one arm location to the next.

Complex positional feedback may not really be necessary. The stiffness of design inherent in the proposed structure may be sufficient for the accuracy required. Present multiple head, paper tape input, numerically controlled drilling machines for circuit boards generally hold hole placement accuracy to about ± .001 inches. The proposed Briareus could comfortably operate with an xy plane reset position accuracy of five times that tolerance, ± .005 inches. Precision is easily achieved in the Z direction because it can be easily referenced to the top surface of the printed circuit board.

One goal for this system is to allow components to be readily removable. This means a complete avoidance of chemicals, soldering, and similar irreversible processes in handling components. We are striving for universality. And, while there is no limit on substrate material, we shall assume a common two-sided, one ounce G-10, fiberglass epoxy, 0.032, 12 inches square or less printed circuit base material.

We will also assume (but not necessarily so) that the design data inputs are via remote terminals connected to a data telecommunications network. A local mini, plus a microprocessor, plus a floppy disk will provide adequate local storage and processing, provided access exists to a larger design processor computer.

A key element of this system hinges on the concept of forming the printed circuit connections by numerically controlled engraving of a copper-clad board. A simple diamond-pointed router can easily scribe out a printed circuit connection conductive path a few thousandths of an inch in width. For example, motion is permitted only along the X direction while holding Y direction constant; then moving on Y while holding X fixed and so forth. Any desired width rectangle can thus be scribed. A connection is merely two narrow, elongated rectangles overlapping on the ends. Of course, a little processing (joint movement of X and Y) can permit arcs to be engraved as well. While the following description assumes manufacture of a single board at one time, a mass production option exists. The engraver mechanism can be used to engrave ruby-lith masters. Here boards could be made by conventional photo or silkscreen etching using the same

numerical controlled program. Several boards could be stacked to save time in drilling. However, these are secondary options. The thrust of the description focuses on formation of a single etched board. A remote computer used in the design process program could convert printed circuit paths into all specific X, Y coordinates necessary to engrave all lines required for the first side of the circuit board. The board is then turned over and the reverse side similarly engraved with its pattern. Following the engraving process, numerically controlled holes are drilled by one or more drill heads or "arms" as appropriate to a machine called "Briareus." To avoid changing drill bits manually, a multiplicity of simultaneously rotating arms for common drill sizes are used. Each drill is depressed into the work piece only on command, as needed. After hole drilling and routing, the board is air-blast cleaned and made ready for insertion of spring clip grommets.

One of the basic goals for this system is to make each component field removable without physically unsoldering components. Therefore a solder-free method of bonding components to each side of the board is needed. While DIPs can be unsoldered, in practice this process is generally inconvenient and may subject the component to hard-to-control high temperatures. Such temperatures tend to shorten component lifetime in an unpredictable manner.

One particularly simple and elegant alternative to soldering is the approach of using conductive elastomer pin grommets. For example, Appendix B describes a grommet system under development by the Avakian Systems Development Company. Basically the Avakian device is an eyelet made of a conductive polymer. A small hole in the center accepts integrated circuit or other dual-in-line package (DIP) pins. A DIP may be removed many times without increasing the resistance of the eyelet. The resistance after multiple reinsertions is said to be less than 15 milliohms. (In a telephone conversation with Avakian he reported that the conductive polymer will be available in early 1975 at a cost of between $5 to $10 per cubic inch. This, he said, corresponds to an eyelet cost of less than 0.5 cents.)

These eyelets (or an alternative concept using hard spring material) could provide a reusable DIP socket that would not require soldering and would permit connections to be made from the foil of one side of a board to the other. Such a mounting arrangement would permit rapid removal of DIPs for testing and reinsertion.

Returning to the description, after the eyeletting, the board would be moved from the eyeletting station to a component insertion station or "arms." The component insertion station in a general purpose system could be readily built to have 1000 slots to hold 1000 different types of DIPs, each contained in their own protective carrier clips. Each carrier might contain about 25 DIPS depending on the length of the DIPs. A push bar would be used to poke the tentatively selected DIP out of its carrier into a combination test and insertion jig. If the DIP passed its test it would be inserted into the plastic eyelets forming a socket.

To simplify the design of Briareus we assume that all components are available in DIP mountings. This would appear to be a reasonable assumption for the future because this is the way electronic packaging is evolving. In cases where components are specified that cannot fit into a DIP socket, then a DIP connector plug may be used in lieu of the DIP. Wires from such a plug could even connect to large outboard devices, such as large transformers and electrolytic capacitors. Interconnections between boards could be handled by using cables connected to DIP plugs.

One thousand DIP carriers may seem like a very big number. But, DIPs are really very small devices and take little room. As a practical matter, three carriers would be set aside for each DIP component type. This would permit one carrier to be completely emptied and feeding start on the next without having to stop the machine to individually refill each carrier as it ran out of chips. The third separate carrier suggested for each DIP type would be used to store rejects. This then cuts the actual number of DIP on-line choices down to about 333 different types for a 1000 carrier slot system. This number would be adequate for fabricating most digital circuits since in the majority of cases DIP components on a single

board tend to be specified from the same chosen families (i.e. 5400/7400 TTL, 4000 CMOS, ECL, etc.) If more different types are found to be needed in practice, two options are open. The first is to increase the size of the chip carrier storage area. The second alternative is to plug in an entire storage unit. Thus, the whole family of DIPs could be replaced in the same manner as changing disk packs in a computer system. This same approach could permit bringing in any unusual DIPs required for production of any odd-ball unit.

One of the key features of the Briareus system would be an ability to test components for gross malfunctioning before insertion. Before board insertion, each selected chip is pushed out of its carrier into a holder transporter and test jig. Built into the carriers would be a single standard or reference chip of the same type of DIPs in that carrier. Parenthetically, the carriers used by Briareus would not be the same as those used by the DIP manufacturers for packaging for transportation. The test jig feature uses conductive fingers to make connections permitting comparison between the reference unit and the chip to be inserted. The Briareus' chip holder would also contain comparison logic and a matrix designating input and output leads for testing. High speed signals are connected to both the inputs of the probationary chip and the reference chip simultaneously. Exclusive OR circuits check the outputs for identical tracking match. An allowable propagation delay is tested by strobing the circuit for test to insure matching or exceeding published delay specification. Only minimal level testing is assumed as all the components would have been tested in incoming inspection as a normal practice. More complex testing could be performed, if required, in the Briareus. For example, each DIP could be transported to a small evaporatively cooled chamber for a low temperature test followed by a high temperature test. It is our present belief that it will be more cost effective not to over-refine the testing operation.

After each component is called up and after it passes all its tests, it is then inserted into the predrilled board through the

conductive elastomer grommets (or a spring metal equivalent). The order of mounting the components is not critical, other than all the vertically oriented DIPs would be inserted at one time. Then the entire board rotated 90 degrees for insertion of the remaining components.

One feature of boards made by this process is that it avoids the special handling required for gold plating edge finger connectors. Gold plated fingers fitting into a molded printed circuit connector have been the classical way of interconnecting printed circuit boards. Today a much cheaper and more appropriate cabling method is the use of flat wire press fit connectors. In a few seconds, using a low cost special tool, all 16 wires in a flat cable can be joined to a single DIP connector. This DIP plug and cable can be plugged into an DIP socket, including boards made by Briareus.

BRIEF DESCRIPTIONS OF THE DRAWINGS

Figure 1 is a pictorial representation of one embodiment of the system.

Figure 2 is a pictorial sketch of the motions and degree of freedom of the worktable mechanism.

Figure 3 is a cross-section view of the drilling and routing head mechanisms used to drill holes, engrave patterns and cut the board edges to size.

Figure 4 is a perspective sketch of the front and rear assembly station elevators used to insert components from component carriers onto specific locations on a printed circuit board.

Figure 5 is a cross-sectional view of the pusher rod arrangement to load a predetermined integrated circuit or other DIP chip onto a transport device.

Figure 6 shows an end view of the DIP chip carrier to be used with this system.

Figure 7 shows the top view of a three chip memory test device for each spearate DIP carrier.

Figure 8 is a cross-sectional side view of the test memory device fitted into the DIP carrier strip.

Figure 9 is a perspective sketch of a thin flexible printed circuit folded to form the test memory device.

Figure 10 is a perspective sketch showing the operation of the transporter holder assembly conveying chips from the DIP carrier onto the printed circuit board.

DESCRIPTION OF THE PREFERRED EMBODIMENT

(In the following we use the standard patent office reference method of a unique number following each designated part. The reference numbers are assigned in monotonically increasing order as each part is referenced and the same number remains with that part.)

The operation of the system may be understood by reference to the figures.

In Figure 1 a metallic framework, 1, approximately the size of a desk provides support for a movable worktable, 2. The worktable, 2, is rotatably mounted along the Z axis on a movable platform, 3, which moves in the Y axis direction. This movable platform, 3, is in turn connected to a main platform, 4, which is movable in the X axis direction.

The raw material that is to be converted into a finished board is normally two sided, foil covered board, 5, which is affixed to the movable worktable, 2. A number of individual drills and routers, 6, operating under numerical control, sequentially drill and mill route holes in the circuit board, 5. After these physical operations have been completed, conductive clips such as conductive elastomer grommets, 8, are inserted onto the board. These serve two purposes. First, they permit interconnection of circuits between the top and the bottom of the circuit board, 5. And, secondly, they hold the electrical components to be added to the board. The grommets used may be made of a number of conductive spring materials including conductive elastomer such as described in the Avakian devices described in the 31 October 1974 issue of *Electronics* magazine. (See Appendix B.)

After the grommets are inserted, DIP chips stored in the components storage area, 9, are inserted onto the printed circuit, 5. This is more clearly shown in the following figures.

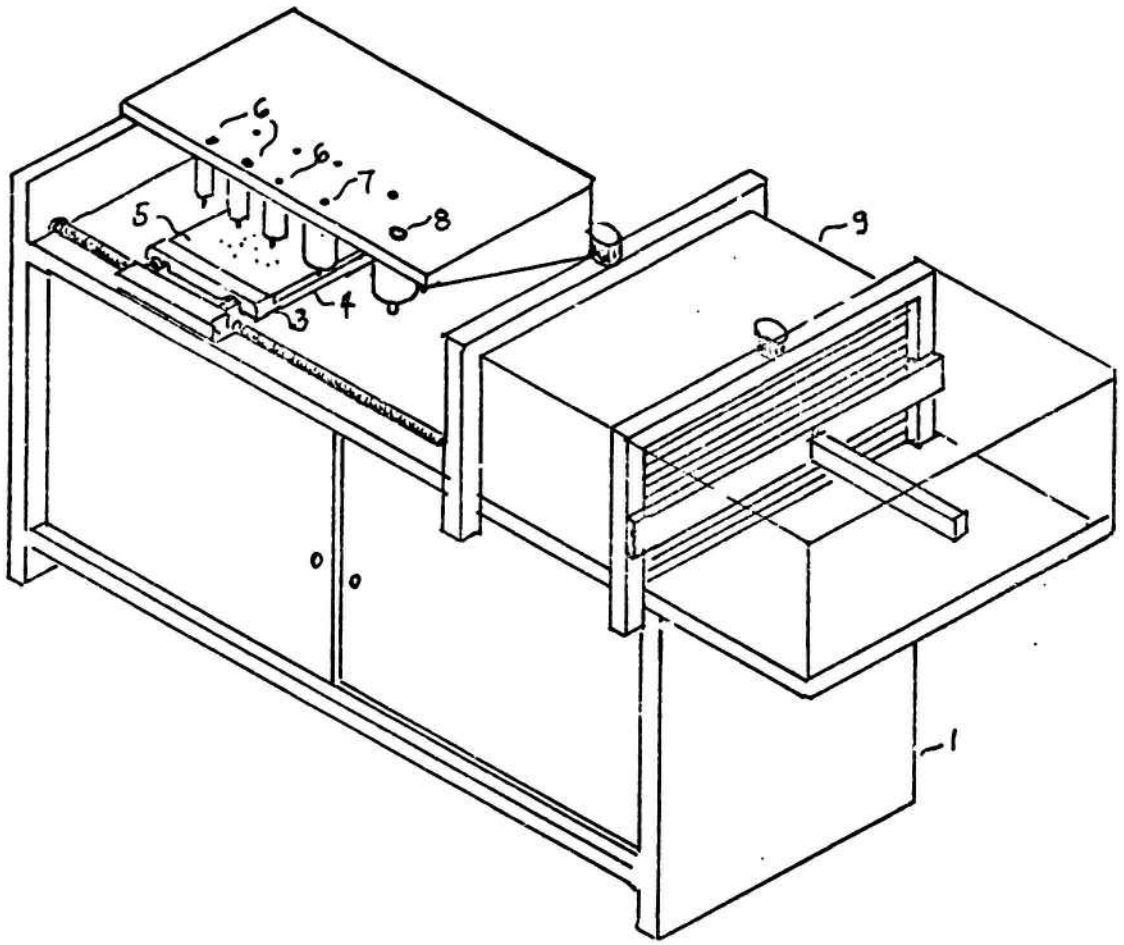


Figure 1. BRIAREUS, mechanism sketch.

Figure 2 is a pictorial sketch of the movable worktable rotatable into one of two fixed positions 90 degrees apart by the rotational drive motor, 10. Motion in the Y direction is under control of a Y direction motor, 11, while that of the X direction is under control of an X direction motor, 12. For the sake of illustration only and not of preferred manner of construction, the motion is shown in the illustrations to be coupled by two worm drive shafts, 13 and 14, respectively. Two positional sensors, 15 and 16, such as optical or magnetic digital encoders provide precise positional references for the table's position relative to the axes of table motion and to the drills, 6, and other heads of the Briareus.

Figure 3 is a cross-section of the drilling and routing mechanisms and shows the drill mechanisms, 6, driving a collet type drill, 17. Changing drills from the top of the assembly is facilitated by the top knob, 18. An electromagnet or similar actuator, 19, forces the drill bit, 20, into the work surface with a controllable force and for a preset distance. A somewhat similar arrangement is used for the routing mechanism, 21, but here a thrust bearing, 22, provides very precise surface reference to assure that the router blade, such as a diamond point, penetrates a fixed small distance into the surface of the printed circuit material, 5, generally only slightly deeper than the copper coating and prevents significant undercutting of the support base of the printed circuit, 5.

Circuit designs are created by computer controlled positioning of the router blade, 23, to form narrow, closed "boxes" forming thin conductive channels between any two or more terminal locations. Line widths and spacings as thin as a few thousandths of an inch should be possible.

Figure 4 shows an arrangement used to feed DIPs onto the formed boards. This mechanism is comprised of a front elevator assembly, 24, and a rear elevator assembly, 25. Two separate drive systems, 26 and 27, are used to raise and lower the elevator in the Z direction. Of course these two separate assemblies, 24 and 25, could be combined into one since they are both commanded to go to the same Z height location. Similarly, the elevator moves sideways by a Y direction

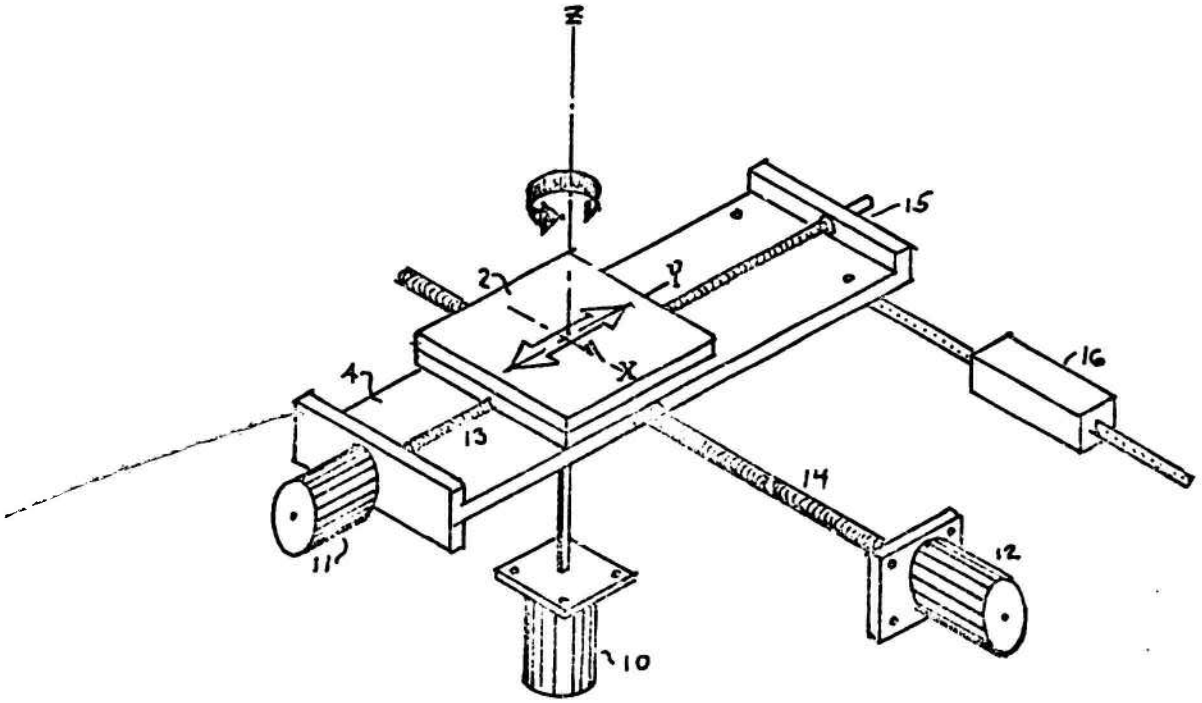


Figure 2. Work table motions.

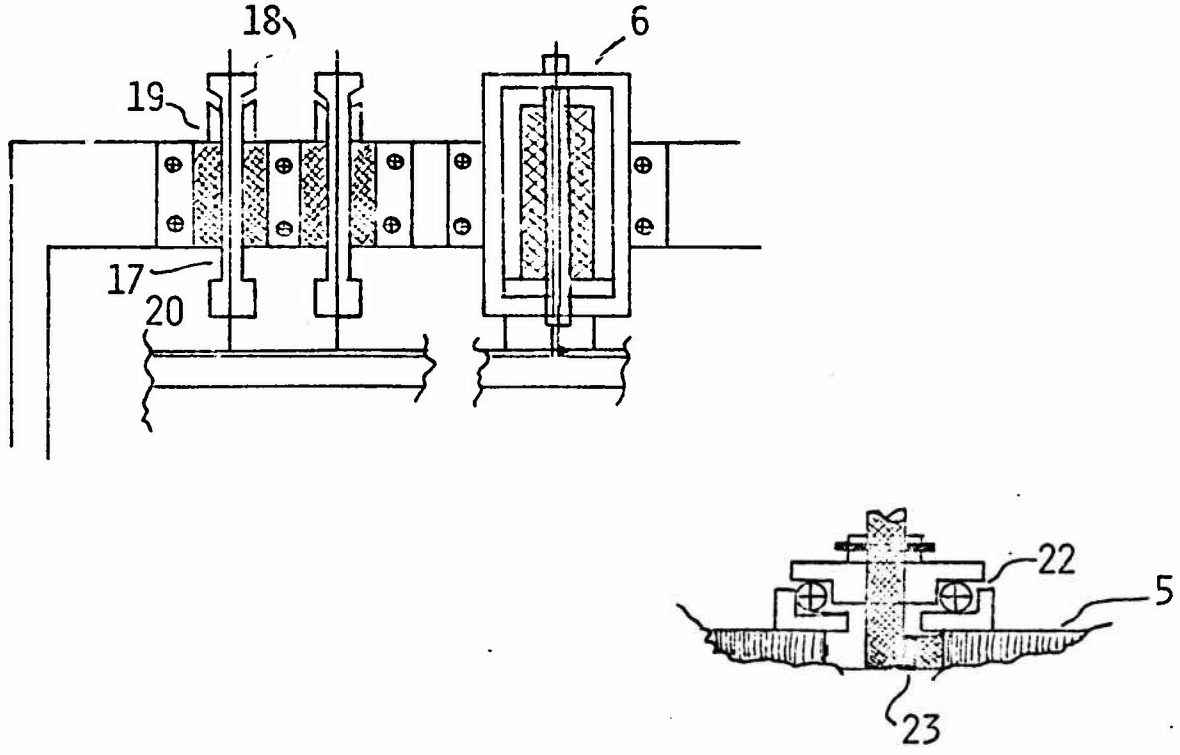


Figure 3. Drilling and routing heads.

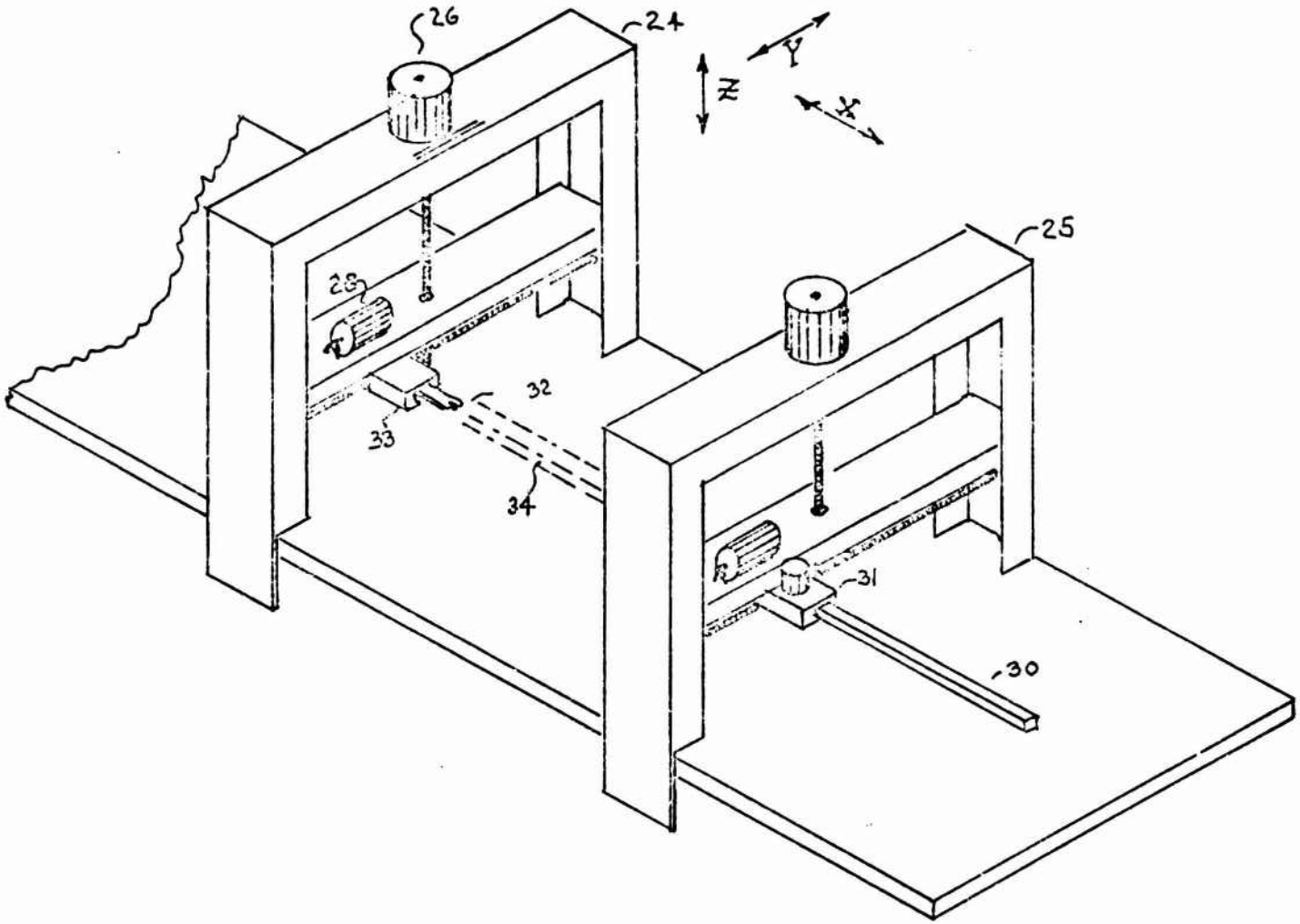


Figure 4. Assembly station elevators.

drive system, 28 and 29. At the rear, an X direction pusher rod, 30, is actuated by a pusher rod driver, 31, forcing an integrated circuit or other DIP, 32, into a transporter holder device, 33. DIPs are conveyed in long stick DIP carriers, 34.

Figure 5 shows a section view of the pusher rod, 30, forcing a DIP into the transporter assembly, 33. Also shown is a guiding indexing device, 33, that insures centering of the transporter to pick up components regardless of minor misalignment of the chip carrier, 34. A protective shroud, 35, provides safety coverage for the pusher rod, 30 that pops in and out of different X, Y, Z addresses, selecting components.

Figure 6 is an end view of the DIP chip carrier. The DIP chips, 35, are easily slid from their normal manufacturer's delivery packages into the plastic body, 36, that forms the DIP chip carrier, 34, which is inserted into this machine. An indexing pin, 37, provides a reference point during chip transfer and hold-down for the memory test device shown in Figure 7.

Figure 7 is a top view of the memory test device, 38. This unit is comprised of a printed circuit holding three DIP chips. The first is a test pattern generator, 40. The second is a comparison circuit, 41, that matches the output of a standard reference chip, 42, against the chip to be inserted. Basically this circuit combines inputs of the chip to be tested with those of the reference chip, and compares output tracking as the input signals are stepped through a range of states. A predetermined time threshold insures that slight propagation time differences do not cause false readings. Connection to the chip to be measured is via a connector, 43, composed of conductive elastomer spots.

Figure 8 is a side cross-sectional view showing DIP chips, 35, in the chip carrier and the memory test device mounted above the chips, 35, stored in the carrier, 34.

Figure 9 shows a pictorial view of the printed circuit, 39, which is the heart of the memory test device. This printed circuit is really a large cross-bar interconnection matrix whose junctions spell out the input and output specifications for the DIP being tested. These

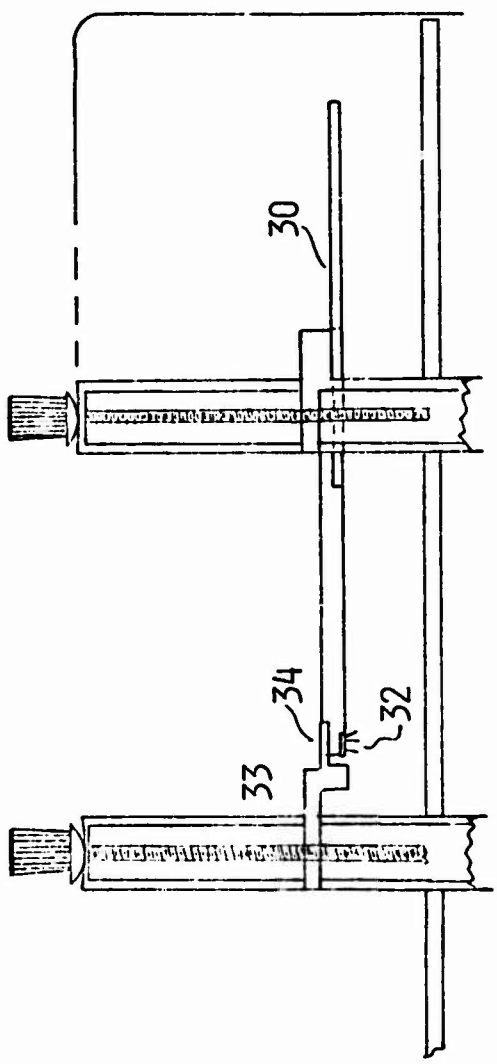


Figure 5. Push-rod arraingement.

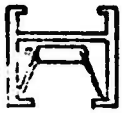


Figure 6. Chip carrier.

Figure 7. Test memory device, top view.

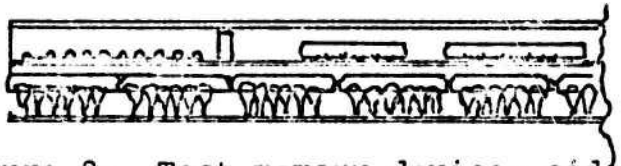


Figure 8. Test memory device, side view.

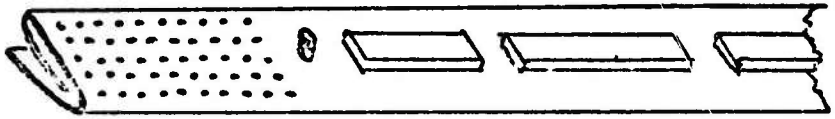


Figure 9. Test memory device, printed circuit.

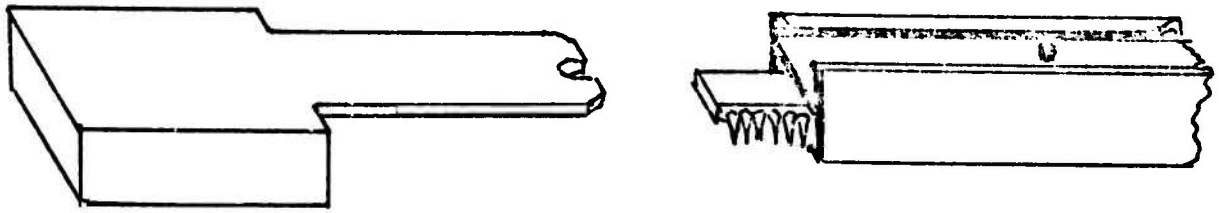


Figure 10. Operation of transporter holder assembly.

printed circuits would be prepared once for each new different type of DIP. The Briareus machine itself is an excellent way of making these specialized circuits quickly and to order.

Figure 10 is a sketch showing operation of the transporter holder assembly, 33. The chip emerging from the carrier is the chip that will be tested and is called the "probationary chip," 41.

Table 1 below describes the steps involved in the testing and insertion of the probationary chip, 41, into the printed circuit board, 5.

Table 1

TIMING DIAGRAM

Step:	FRONT ELEVATOR	REAR ELEVATOR
1	Line up transporter along Y-Z axes.	Line up pusher along Y-Z axes.
2	Insert transporter until solid contact is made.	
3		Push rod in X direction corresponding to expected length of DIP.
4	Close side of transporter until DIP leads are bent to fit shape of transporter side plates.	
5	Start electrical circuit testing.	
6	If successful completion of electrical tests measured move to proper Y position	
7		Withdraw pushrod.
8	Lower chip into board by moving solely in the Z direction.	
9	Release chip.	
10	Raise transporter in Z direction to next chip position.	

Figure 11 is a signal block diagram of the system. Connection to the outside world is made via a telephone line to one or more

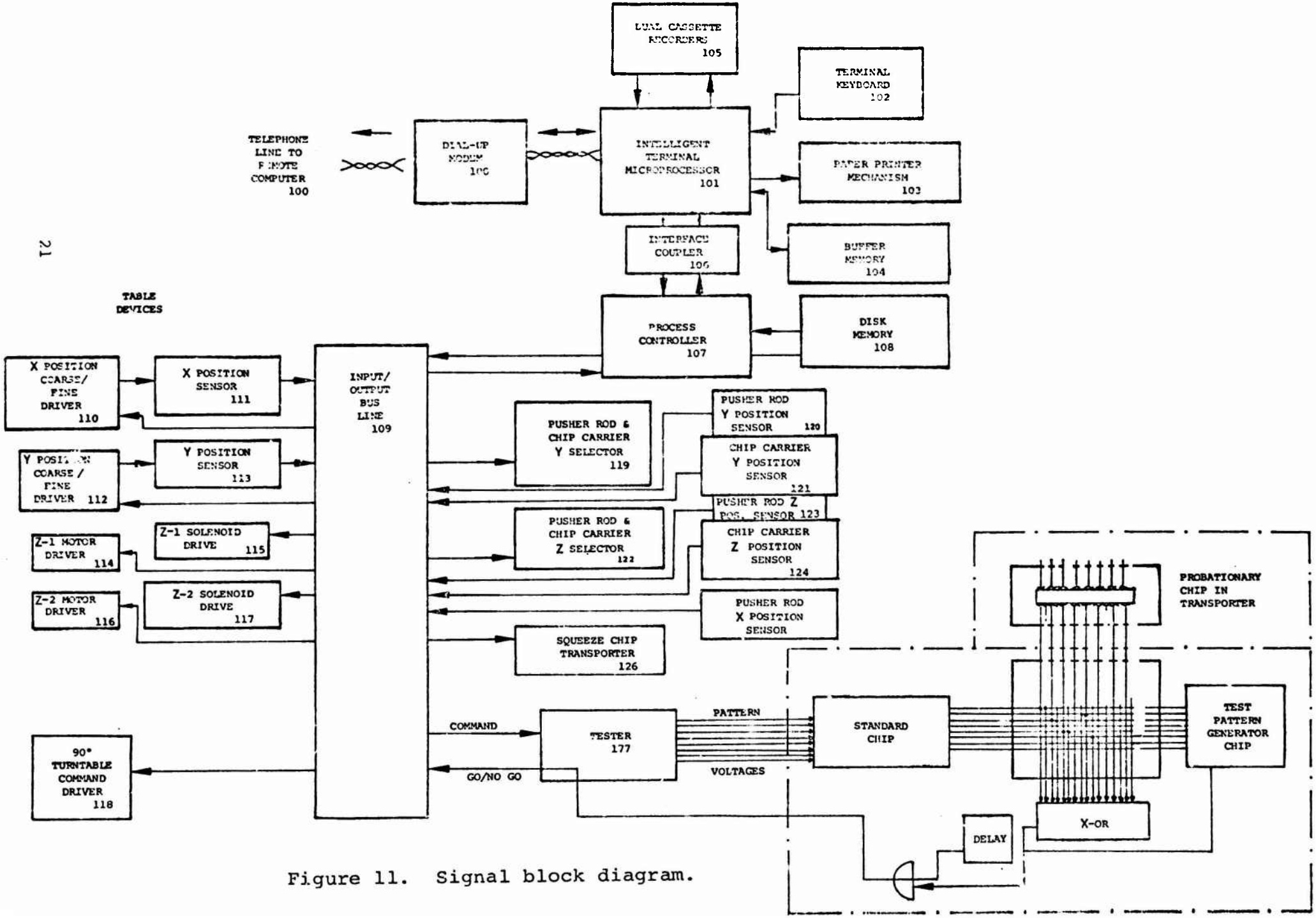


Figure 11. Signal block diagram.

remote computer installations or to remote terminals. Any conventional design automation approaches can be used remotely to generate the required interconnection data and specify the parts. One means of communication might be via a dial-up modem to an intelligent terminal microprocessor. Connected to this unit is a terminal keyboard, 102, and a paper printer mechanism, 103, although a cathode ray display can be used as well. Also connected to the intelligent terminal microprocessor is a small buffer memory, 104, to smooth out the asynchronous arrival of data to the outside world, and to and from the Briareus mechanisms. The interface coupler, 106, connects the intelligent terminal microprocessor, 101, to a small full-time dedicated process controller, 107. While these two units, 101 and 107, could be combined, it is easier to program two separate units configured to perform each function most effectively. Connected to the process controller is a disk memory for on-line storage of circuit path descriptions, hole coordinates, test programs, etc. The process controller, 107, interconnects with a common-bus-organized transfer bus line, 109. Also connected to this bus is an X position driver under control of the process controller, 107. And, closing the feedback loop for this X channel is a position sensor, 111. The driver, 110, provides power until a suitable null comparison from the sensor, 111, is received in comparison to the command value from the process controller, 107. Similar arrangements are used for the Y axis, 112 and 113. The Z drive is somewhat simpler as the drills and router only have to move between two fixed positions. Power is applied to the motor by the driver, 114, well in advance of need, and a solenoid, 115, is operated to pull the drill into the printed circuit, 5, being cut. A series of separate Z motors are used, 116 and 117, as each in turn is depressed as needed. A simple fixed 90 degree rotational motion perpendicular to the Z axis permits chips to be mounted either horizontally or vertically for maximum freedom of component layout. This is performed by the turntable command driver, 118.

The next set of functions deal with the chip insertion. These are the pusher rod and chip carrier Y selector, 119. And, the feed-

back here is controlled by the push rod Y position sensor, 120 and 121. Similar arrangements exist for the Z direction, 122, 123, 124 and 125. Opening and closing of the chip transporter to squeeze chips to fit is controlled by the squeeze chip transport module, 126. And, lastly, the tester circuit, 127, is operated to command each chip to be tested on a probationary basis, as previously described.

APPLICATIONS

In the following we consider ways that this system might be used. To model the operation we must make some assumptions:

1. A number of Briareus machines will be installed. Some will be at contractors' sites and some at government armories to manufacture boards on a pre-determined pricing formula.

2. Each site is tasked to manufacture equipments for a set of authorized users and mail the resulting equipments by air or United Parcel Service to those users.

3. Each site is connected by a digital communication network to its community of users and to other computer sites.

4. We shall consider three different general classes of users for discussion:

   a. The electronic equipment user who calls upon the center as a general purpose repair depot, which will either repair a defective circuit board or provide a replacement board.

   b. The remote circuit-designer user who designs circuits on paper using on-line computers connected to the network.

   c. A user who has large standard orders for revision of boards superceded by engineering changes. These jobs are scheduled for "background" or time not otherwise required.

Let us consider each class of users separately.

AUTOMATIC REPAIR

The first of our hypothetical users is a man (or woman) who works nearby the center. And, he (she or it) brings in a circuit board that does not work. The operator inputs the board number, its serial number and its last revision date to his terminal. A local memory search is made. Assuming that the local center does not have the full board description available locally, it calls a

remote computer center for the data it needs to describe the board. This data is transferred to local memory. The local program then searches its local memory for its inventory of DIPs to be sure that it will have all the components needed to test and/or fix the board. If any circuit elements are missing, there are two or more alternative choices. First a check could be made of other, preferably nearby, centers to see which had all the needed elements. If one or more does, then there is a second decision to be made. Should the unit be sent to that remote site or should, instead, the parts be ordered from the nearest parts distributor. In the latter case, it would be helpful to have the terminal portion of the system have access to a network capability of preparing the purchase order and transmitting it with a request for a verification and target delivery date. Assuming that the parts were in hand, the most desirable case, we would proceed and place the suspect printed circuit board onto the worktable. Two or more reference holes would be indexed to insure proper line-up with the local definition of the hole positions and the machine would be set to the "automatic test" mode. Now the circuit board is positioned under the testing elevators, and DIP components are sequentially removed, each being tested for specifications. If a defective or marginal DIP is found, it is removed and a new one used as a replacement. This takes care of failures in the DIPs themselves. But, what of the board itself? Here the elevator could use a two test cable configuration test. All DIPs would be temporarily removed. The first test cable is plugged into the first hole, while the second test cable is sequentially inserted into every other DIP socket. This should then catch any opens, shorts or cross connections on the board. But, what about some very marginal situation that happens every now and then? Here we have two alternatives. The first is to fall back to a human being type technician and hope for the best. The second, and cheaper way is the brute force approach. A new board is cut and assembled. If that doesn't work, then the trouble is elsewhere — possibly the design, and the initial designer deserves a call. He may already be made aware of similar problems if this is a flaky design case.

NEW DESIGN CASE

Joe engineer is a graduate student and has an idea for a great new blackbox needed for an experiment he is conducting under an ARPA grant. It would permit his present terminal to do all sorts of wonderful new things. Joe is not very familiar with on-line automated design programs and would rather do it himself. So, he inputs a wiring and component list to the center. His is a low cost, low priority background job. The Briareus center schedules this job in the queue for an off hour. Joe is unsure of himself, so he asks for a paper print of the circuit, since he doesn't have access to a machine with precision graphical output. He wants to see the circuit exactly as Briareus sees it. The center would run the same program for making a board, but instead calls a programming routine using a pen to draw a picture of the device on paper instead of copper-clad board. Of course the sophisticated user wouldn't think of using anything other than a fancy CRT and releasing the design directly on-line. But with Joe's low budget, he is happy merely receiving a precise drawing of all the wire paths by mail a few days later. A week later Joe finishes making the few changes that are needed. He then says "go ahead" on-line and the center then proceeds to make up the board with all chips in place and sends it in the mail to him that day.

ENGINEERING BOO-BOO

The last example of hypothetical sample users we consider here are those that should receive in-field retrofits for design changes, which are rarely implemented in practice. Almost every blueprint for a complex assembly contains space for a list of revisions. This list grows rapidly during the first few months the drawings are released. Some changes are obvious improvements. But many others are needed to correct gross errors or incipient problems. Some necessary or desirable changes do not manifest themselves until many months after the equipment is in the field. The Nader-inspired idea of recalling automobiles is quite new. And, these recalls are limited to safety defects. In the good old days a defective bolt

in a steering column was ignored under the gracious doctrine of caveat emptor. We still practice "buyer beware" with computer circuits. There are many "flaky" circuit boards in use in sold equipments today. Most manufacturers prefer to avoid the issue until the warranty period expires or, preferably, forever. The reason is simply the very high cost of field retrofits.

The Briareus system could permit economical improvements to the equipments after the equipment has left the factory doors. Even new boards could be cut and used for replacements while the partially defective boards are dismantled and then parts salvaged for the next unit. This becomes economically feasible because of the low potential cost of cutting a single board, disassembly of components, and assembly and checkout using Briareus.

ECONOMIC ANALYSIS

MICROANALYSIS

It is always hard to estimate the payoff for an entire new technology as it is necessary to make assumptions. And, conclusions can never be stronger than assumptions made. In the following we have assumed the following:

1. That the full costs of all development work leading to the serial production of the Briareus equipments is less than $2 million and that this will be amortized over 100 units.

2. Once significant production has begun, the per unit price will be $100,000 or less, plus $20,000 amortized development cost, or a total price of $120,000.

3. Table 2 shows a total annual cost of $38,000 per year under the following assumptions:

   a. $20,000/year is spent for capital payoff amortization.

   b. The equipment has a useful life of five years.

   c. Maintenance costs = $12,000 (10% of initial price) per year.

   d. Interest is 10% of amount outstanding.

Table 2

ANNUAL COST OF BRIAREUS

Year	Capital Remaining	Capital Payoff	Maintenance Exp.	Interest @ 10%
1	100,000	20,000	12,000	10,000
2	80,000	"	"	8,000
3	60,000	"	"	6,000
4	40,000	"	"	4,000
5	20,000	"	"	2,000
		100,000	60,000	30,000

Annual cost, $\frac{\$190,000}{5} = \$38,000$

4. Although this machine can backlog work and work off-peak for non-rush jobs, that the average uptime workday for cost estimation is 8 hours, 5 days per week, excluding holidays. This really says that the machine is only available 2060 hours per year (in lieu of the 8760 hours in the year). This equates to a per hour cost of $\frac{\$38,000}{2060}$, about $18.44 on a one shift basis.

5. The machine requires an operator. We assume a rate of $7.00 per hour plus a 100% overhead, or $14.00 per hour.

6. In Table 3, below, we consider the times and implicit costs to manufacture a hypothetical board containing 30 DIPs each with 20 holes.

Table 3

COST OF MANUFACTURING A BOARD USING BRIAREUS

	Number of holes:	Operations/Sec	Seconds	$
Drilling	30 DIPs x 20 holes/DIP ≃ 600	1	600	3.07
Routine	600 lines @ 1.5" x 2/inch 1800 inches	5"/sec	360	1.84
Eyeletting	600	2	300	1.54
Component Testing	30	1/3	90	.46
Assembly	30	1/4	120	.62
Repair	1	1/10	10	.05
			1480	7.58
			Machine operator @ $7.00/hr + 100% overhead	= 5.74
			TOTAL COST	$13.32

7. Now comes the hard part; estimating the labor required to fabricate and test one or a few equivalent sized boards by manual means. As a gross estimate we use a figure between 5 to 100 hours. 25 hours at about $8.00 per hour appears a reasonable central estimate. Under the previous burden formula, this equates to $400.

8. Using the above estimates, then the overall benefit to cost ratio is on the order of 30 to 1.

9. More importantly, the intangible benefits far exceed the visible dollar labor savings. We see a significant change in the way that electronics equipments can be designed, manufactured and serviced. These are benefits in being able to get equipment when you need it rather than several years later. It means that new equipments can be manufactured in very short runs economically permitting a very much wider range of equipment options and permit supplying equipments that simply would have been prohibitive before.

MACROECONOMICS

We seek to address the question, "How much can DoD save if it successfully pursued this line of development?" "Savings" may be an excessively elusive quantity and misleading as a concept. As a practical matter, any savings are resources that can be converted into more usable defense expenditures. As was shown in Volume I of this Final Report, national defense capability is most likely to continue its past trend limited to a constant dollar level in the future. This combined with inflation and increasing GNP means that the defense establishment may be expected to continue the long run trend of receiving a decreasing percentage of GNP. As labor costs tend to rise almost as fast as GNP, the short end of the stick becomes shorter and DoD must learn to make more efficient use of labor relative to capital if it is to maintain even present levels of effectiveness.

Now let us consider the Defense budget and the costs of electronics. Of the $15.3 billion being spent for electronics by DoD, $4.1 billion is going into research and development, $5.8 billion into procurement and $5.4 billion into maintenance.

The Briareus system can be seen to offer savings in each of these three categories.

Using the gross estimates from the previous section, it was seen that each machine installation had a capability of generating value added of about $400 $\times \frac{3600}{1480}$ = $973 per hour at an hourly cost of about $32.43. This then translates into return on the order of

$2,023,840 per machine each year at a cost of about $66,811 or a net "saving" of about $1,957,029. Now let us assume that the 100 machines (used as the basis for amortization of capital costs) is the number of machines that are created and in use. How reasonable is this? This would mean a cost saving of each machine of $1,957,029 per year or $195,702,900 total. This number might appear to be very large. But, let us compare it to the $15.3 billion figure. And, it is only 1.25% of this number. This is a very small percentage indeed. As a first-cut reasonableness check, let us ask the question, "Would 1.25% of DoD electronics be suitable for replacement by Briareus techniques?" And, our visceral feeling is, "At least that."

Of course these are very gross estimates. They only can set the ballpark target. We need much more accurately refined numbers than that. We need to know exactly where, and how such a system is and is not usable. And, we need much better estimates of the economics and alternative tradeoffs. This must come later. Our objective here was to provide a very rough estimate of payoff to see if the idea was worth exploring further. And, it clearly appears to be so.

Appendix A

ON IMPROVED PROCESSING CAPABILITY OF INFINITELY VARIABLE INTERCONNECTION PATH STORAGE: THE CONCEPT OF MEDIUM VERSUS MESSAGE STORAGE

As part of the formulation of the Briareus concept we asked ourselves, "What is the impact of such a new capability on increased system processing capability for a fixed number of processing elements? And, what might this mean to future computer system architectural designs?"

Intuititively we knew that we would be able to build a more powerful processor with the same number of active elements because we could tailor the system to better fit the requirements. But, exactly how much better? We seek, if possible, to obtain some insight in quantitative fashion for an upper bound for potential system performance.

Let us start by first considering interconnections between elements as a form of "medium" data storage, in distinction to the more usual common concept of "message" storage associated in addressable memory structures such as RAMs, ROMs, disks, magnetic tape, etc.

As a simple numerical example, consider a simple information processing machine which is composed of ten 14 lead processing elements. Say each has seven inputs and seven outputs. The number of potential different simultaneous connections between the 7 x 10 inputs and the 7 x 10 outputs is $\frac{70 \times 69}{2} = 9730$. This means that if we had to have the capability of being able to connect any output circuit to any input circuit, we would require exactly 9730 potential independent cross-point switches. And, each cross point would have to have a 1-bit memory to indicate whether the switch point is open or closed. Let us think of the 9730 bits required to define the switch points as bits of "medium" memory. If we were able to buy "medium" storage cheaply, we could have a very powerful capability of being able to custom structure a computational engine to fit the problem being solved. For example, consider the work on Fixed plus Variable (F + V) configurations studied by Estrin et al to visualize the potential power for such

a configuration — provided it were technically feasible to rapidly specify and construct and modify such configurations. Consider the ILLIAC-IV. Even the limited amount of flexible path interconnections primarily limited to adjacent matrix elements in the ILLIAC provides an insight into the tremendous increase in processing capability (for some sorts of problems) that can come about with a relatively modest amount of parallel path choices.

Present day logical chips, say on DIP packages, can have a great deal of computing power. To fully utilize this power we need simultaneous parallelism. And, this is what the concept of medium storage gets at. It specifies the degrees of freedom of parallel path choices. For example, imagine a configuration like the ILLIAC, but where each module can be connected to any other module (not only its neighbor or limited number of bus lines). You can see that the potential for increased parallelism is greatly increased.

Let us consider as another example a machine with 1000 DIP elements, again each having 7 pins input and 7 pins output. Using our simple equation we can see that the implicit amount of medium storage has increased to (7 x 1000 x 7 x 999) = 48,951,000 bits, or roughly the square of the number of inputs/outputs. That is an awful lot of bits of path choice. And, we do not presently know how to build small, cheap cross bars commensurate with the size of DIPs with the capability of changing paths. But, using Briareus we can rapidly generate a printed circuit to interconnect large numbers of elements such as these. As a practical matter we can usually take advantage of the sparseness of the interconnection matrix that occurs with any regularity of the processing configuration. This is just another way of saying that the storage requirement is drastically reduced if we consider just storing "1"'s and by equating no connection state as being synonomous with "0"'s — which is what we do with conventional architecture. But interesting new possibilities open up when we are now able to whip up a custom

printed circuit board quickly on demand. There is a potential increase in computing power to computing systems that can occur with such flexibility of interconnections, and a useful research topic might be refining this simple exercise to better define the potential for improved processing inherent in the concept. The writer hasn't seen this notion formalized and with a new technology available, it might be useful to do so.

Appendix B

ROLE OF CONDUCTIVE ELASTOMERS

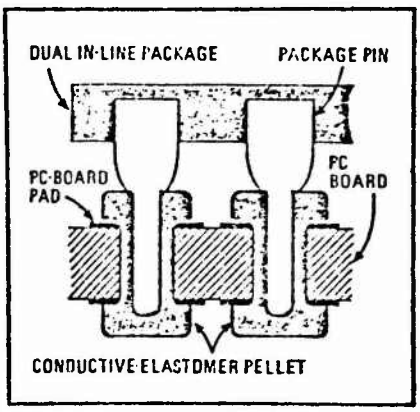
(Reprint)

Role of conductive elastomers expands to p-c boards and connector designs

Working with conductive elastomers, the rubber-like silicone material in which suspended metal particles conduct electricity, a consultant in Glastonbury, Conn., says he's developed a trio of interconnection schemes that greatly simplify the fabrication of printed-circuit boards, wire-wrap-equivalent panels, and electrical connectors.

Emik A. Avakian, head of Avakian Systems Development Co., says that for printed-circuit boards, the elastomer is formed into short, pellet-like cylinders, which are plugged into the holes in the boards, as shown below, left. Component leads are fastened to a board simply by pushing them into the pellets.

The springy, elastomeric material, a proprietary mixture, holds the device pins firmly in place, eliminating, says Avakian, the need for device sockets and plated-through holes, as well as soldering or wire-wrapping. A "head" on each end of the pellets contacts the conductive pads on either side of the board. And, in some applications, the material's high heat-conduction allows heat sinks to be eliminated, he says. Until now, conductive elastomers have been restricted to use in custom microcircuit interconnections in such devices as watches with liquid crystal displays [*Electronics*, Sept. 19, p. 122].



Push to mount. Conductive-elastomer pellets inserted in the holes of a p-c board do double work. They contact the board's pads without soldering, and they hold the components securely in place.

Contact resistance between a pellet and an embedded component pin is low—usually less than 15 milliohms. And if a component is removed and re-inserted as much as a dozen or so times, the contact resistance will increase by only a few milliohms. Moreover, each pellet can carry at least 3 amperes of current with no increase in temperature. The pellets are also self-healing, so that when a component is withdrawn, there is almost no sign of the holes made by the pins.

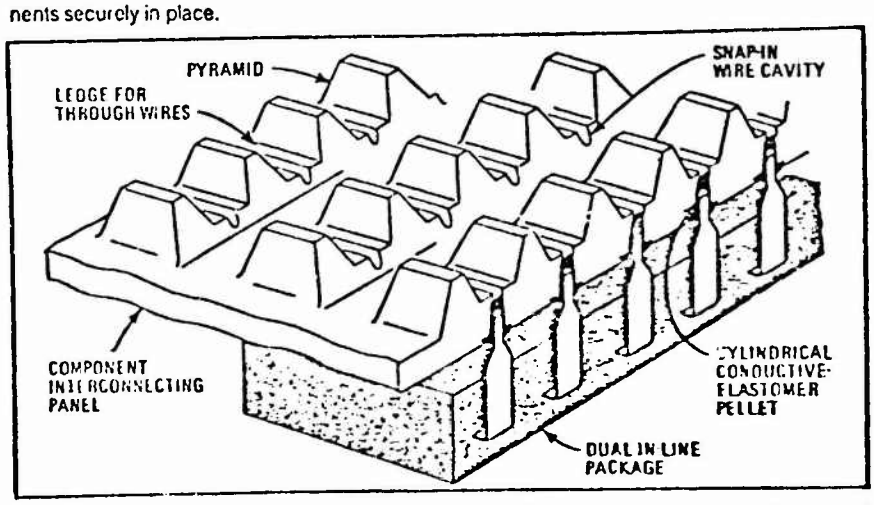
Interconnecting panels. Avakian calls a printed-circuit board outfitted with his pellets a component-interconnecting panel. Pellets can be either molded in place, or they can be formed separately and cured in a long string with their heads connected by a nonconductive webbing. The pellets are then pushed into the board holes in much the same manner as conventional p-c connector pins are staked into a board.

Another type of interconnecting panel that Avakian has developed is essentially an equivalent for wire-wrapped panels. The panel itself is molded from a dimensionally stable plastic, such as Valox or ABS. On its component-mounting side, there is a matrix of holes, with centers spaced on a 100-by-300-mil grid. Each hole has a shoulder that prevents a pellet from being dislodged after it has been inserted and cured. As with the other panel, these pellets are cylindrical, too, and component pins are pushed directly into them.

However, on the other side of the board, as shown at the right of page 26, is a molded array of pyramids and channels. Interconnecting wire, stripped at its ends, is pushed into a pellet and its insulated portion snapped into a cavity at the channel's bottom. The cavity, designed for #30 American Wire Gage wire, provides the same holding force as is required to pull a wire from a conventionally wire-wrapped post. For a through interconnection, the wire is led upward from the snap-in cavity to a ledge along which it runs through the channel.

Avakian is also applying the elastomer pellets to general-purpose connectors. There are no male or female parts in these connectors. Instead, both halves look identical. They are outfitted with elastomer pellets protruding slightly above each connector face. Connecting wires run in through the back of each connector half and are embedded in the pellets. The holes for the pellets are tapered to make a reliable, strong contact between the pellet and the embedded wire. No special crimping tools are needed. The connector can be mated simply with a clamp or other mechanism that pushes both halves, and the embedded pellets, against each other.

Avakian is considering manufacturing some of his systems himself, and he hopes to offer licenses through Epis Corp., another firm in Glastonbury. He will manufacture and sell his conductive-elastomer material. □



No wirewrapping. Molded plastic panel has a matrix of pyramids and channels interspersed with through holes. Conductive-elastomer pellets contact and hold component pins, while the channels act as guides for the insulated interconnecting wires.

Appendix C

STATE OF THE ART AND BIBLIOGRAPHY

The literature of the key fields impinging upon the proposed development is so extensive that we prefer to list key impressions, upon reviewing this material, in lieu of a complete annotated bibliography.

GENERAL LITERATURE SEARCH

Nothing like what is proposed could be found in the literature. However, the key elements of the basic technologies needed to build Briareus into reality are generally in place. The quality of the bulk of papers examined was excellent; but their number excessive. Most dealt with trivia. Publication of the intellectually interesting by operationally limited approaches were the rule.

Very detailed reports on the more interesting operationally useful systems were lacking. It appears that the better work is kept under wraps for use solely within a company internally. In such cases only the results are described. For example:

> ...automating this process the cost of producing the NC tapes to drill a circuit board was reduced by approximately 90%...
>
> ...The cost of producing the process drawings was reduced by 70%...
>
> ...Producing the program for bare board test automatically has resulted in a monetary saving of 90% and a reduction of turn-around time of approximately one week...
>
> ...33-50% cost reduction in schematic drawing and parts interconnect list generation and a 70% reduction in the cost of making changes to the schematic drawing...
>
> ...The economic benefits derived from the overall automated design-build cycle amounts to better than 45% of the costs before automation was introduced. A reduction in turn-around time of approximately six weeks has also been a benefit of our automation system.*

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* Donald L. Peterson, "Automated Design and Manufacture of Printed Circuit Boards," *11th Design Automation Workshop: Proceedings*, (New York: IEEE, Inc., 1974) p. 125.

DESIGN AUTOMATION LITERATURE

The writers on design automation have been prolific, but the number of papers reported in their key publication, *Design Automation Workshop Proceedings*, appears to be falling off every year (with the exception of 1974) since peaking in 1968.

As a practical matter we assume that all the steps of design automation assumed are within the state of the art, but at a high price in computer time. A change in the economics is needed to make it economically feasible for more users.

Although design automation using computers is effective, so are people. A general trend in the literature emerging is that the combination of the two is best of all. For example, the combination of a human being plus computer working together in an interactive fashion is described in a sample recent paper:

> We have demonstrated that for the logic graphs studied, using the interactive-iterative improvement techniques described in this paper it is possible to achieve partitions better than those achieved by other known methods. The key lies in the fact that powerful algorithms are coupled with user experience to form an integrated man-in-the-loop system. Those tasks best done by computer are done by computer and those value judgement decisions best made by man are done by man....
>
> The system, while an experimental one, demonstrates the power available when man and machine are joined together through an interactive system which employs the strength of both.*

A major point in the literature is that all highly automated systems in industry appear to be for batch fabrication only. Although one article by people from Westinghouse mentions that it is cheaper to build more than two units with their batch designed system than doing it by hand, its thrust was clearly mass production.

NUMERICAL CONTROL LITERATURE

The art of numerical control is highly developed and becoming stable. There are a sizable number of books in the field including

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* M. Hanan, A. Mennone and P.K. Wolff, Sr., "An Interactive Man-Machine Approach to the Computer Logic Partitioning Problem," *11th Design Automation Workshop: Proceedings*, (New York: IEEE, Inc., 1974) pp. 76-77.

a users handbook. There are at least 32 languages in present use, but the most common language for numerical control is APT or one of its closely related offspring.

Table C-1

NC LANGUAGES IN USE

ADAPT	AUTOPRESS	CLAM
APT	AUTOPROMPT	COCOMAT
UNIAPT	AUTOPIT	BSURF
IFAPT	AUTOSURF	MILMAP
MINIAPT	SPLIT	PAGET
EXAPT	SNAP	PMTZ
CINAPT	CAMP	PROFILEDATA
APTLOFT	PRONTO	NUMERISCRIPT
AUTOSPOT	INCA	FMILL
AUTOMAP	SYMPAC	ACTION
AUTOPROPS	2CL	ZAP

Source: W.E. Mangold (See Ref. #83), p. 102

Only a few of these languages are widely used:

Table C-2

USE OF NC LANGUAGES

The figure against each language is a percentage of the responding sample (of one U.S. survey in 1968)			
APT	44	SPLIT	9
AUTOSPOT	20	Proprietary	28
AD-APT	15	Other in-house	18
FORTRAN	12		
Original source: The American Numerical Control Society 5th Annual Conference Proceedings 1968.			

Source: I.D. Nussey (See Ref. #83), p. 192

The above charts and other data suggest a significant percentage of numerical control applications are in-house efforts without any attempt for compatibility.

The numerical control languages that are in use (and our survey is not as complete as we would like it) are not very good for integration across the design/manufacturing interface. These NC languages

tend to be very COBOL-like — namely, highly verbose English-like language is used for coding to force the coded program to be easily readable. A much more compact notation scheme would be more useful for interfacing with other programs.

The numerical control systems built to date have not tried to combine many separate functions and different purpose heads into a single unit. Thus, a multiple head driller would only drill.

As one might expect with a 1958 technology, the standard input medium is eight hole punched mylar tape.

The software tends to be compiled or interpreted on a large machine for generation of code to control simple commands. And, most NC processor programs are primarily optimized for calculating cutting of complex curved surfaces. The language processor required is much simpler if only point to point processing need be considered. Table C-3 shows the approximate computer size for various type tasks.

Table C-3

IBM SYSTEM/360 NUMERICAL CONTROL SYSTEM

Program	APT 360A CN 10X	AD APT/ AUTOSPOT 360A CN 12X	AD APT/ AUTOSPOT 360A CN 01X	AUTOSPOT 360A CN 08X
Core size	256K OS	128K OS	64K DOS	32K DOS
Full 3 axis and multi axis machining	(3D rout)			
APT point to point				
System macro				
Macro				
Advanced arithmetic and logic				
2½ axis continuous path machining	(2D rout)	(AD APT)	(AD APT)	
Limited computation				
Point to point and slope arc milling		(AUTOSPOT)	(AUTOSPOT)	(AUTOSPOT)
Copy and tracut				
Edit				
CL File				

Source: I.D. Nussey (See Ref. #83), p. 192

AUTOMATIC TESTING LITERATURE

Much of the literature on automated testing is concerned with the problem of uniquely, unambiguously pinpointing a failure to a

single defective element. Since the concept of Briareus detects only to the chip level, it simplifies the tester design problem. Most of the literature in the field is irrelevant to the problem of simple go/no go replacement of a significant digital logical unit.

A first impression that one receives in reviewing the literature of automated fault testing is that it is a very complex and expensive business. However, if one assumes the Briareus simple test philosophy, the problem becomes tractible. We need merely replace a board when we can't find the marginally bad chip that we can't reject forthwith and which doesn't work.

There are many other evaluative tests that could be run on a board that we intentionally do not consider. The payoff for doing so simply isn't worth the cost. As a fallback position, we could always connect a very high priced board tester cable to a Briareus arm and program it specifically for the board and DIP in question. But it is doubtful whether the payoff would warrant the expense. The error detection philosophy must match the system design philosophy.

One clear limitation of the considered testing method in Briareus is that it will have to be modified to handle non-digital logic components. There is an implicit assumption in Briareus that all components used will have gone through a thorough test via a general incoming inspection line machine. The assumption also presupposes that the chance of a defect is rather small to start with in the first place. And, most equipment in the future will be solely digital logic. These assumptions will, of course, be modified and the machine changed accordingly if analog testing is also needed.

BIBLIOGRAPHY

The bibliography on the following pages is arranged in inverse chronological order. The fields are relatively dynamic. Recent works are placed at the top because they tend to be more valuable than earlier ones. As numerical control is so stable an art, we have limited the bibliography on that topic to books. We have also

left out almost all the literature on automated layout for LSI elements because it is a bit off our mainstream interest here.

Each of the entries is marked to indicate whether it relates to design automation (DA), numerical control (NC) or to automated testing (AT).

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